

HIGH-PRESSURE SENSOR FOR PRESSURE-INDEPENDENT  
TEMPERATURE MEASUREMENT

## Technical Area

In addition to piezoelectric quartz crystals, sensor chips are being used today as combustion chamber pressure sensors. When used to detect the pressure prevailing in the combustion chamber of an internal combustion engine, the silicon chip must not be exposed directly to the high temperatures prevailing there, which are on the order of approximately 600°C. This is accomplished with the help of a metallic separating diaphragm and a welded ram of a sufficient length. By micromechanical application of a tiny platform at the center of the diaphragm, the sensor becomes a force sensor.

## Background Information

A combustion chamber pressure sensor designed as a sensor chip is known from the *Bosch Automotive Engineering Manual* (chief editor Horst Bauer, 23<sup>rd</sup> updated and expanded edition), Braunschweig, Wiesbaden, Vieweg 1999, ISBN 3-528-03876-4, pages 110/111. To prevent the silicon chip from being directly exposed to the high temperatures of max. 600°C, a metallic separating diaphragm and a welded ram having a length of a few millimeters are provided. Compressive forces applied by the front diaphragm are introduced into the sensor chip via the ram and through the platform with little additional distortion. In the retracted installed position, the sensor chip is only exposed to operating temperatures below 150°C.

The semiconductor pressure sensor illustration on page 110, bottom of the right-hand column, shows a bridge circuit which receives a power supply voltage  $U_0$ . The bridge circuit includes shunt resistors  $R_1$  which are stretched under stress and shunt resistors  $R_2$  which are compressed under mechanical stress on a silicon substrate to which they are applied.

Whether applied to a steel diaphragm or a silicon diaphragm, piezoresistive high-pressure sensors designed in this way and based on an elongation measurement are used in numerous systems in the automotive field, including direct gasoline injection, high-pressure storage injection (common rail), driving dynamics regulations and electrohydraulic brakes. Future use of piezoresistive high-pressure sensors will be in cylinder-selective pressure measurement in the combustion chamber of an internal combustion engine.

For the pressure measurement, multiple resistors are provided on a suitably dimensioned steel diaphragm and are connected in the form of a Wheatstone bridge. By elongation and/or compression of the resistors, the Wheatstone bridge is tuned, yielding an electric signal proportional to the acting pressure. In addition to the desired pressure dependence of the bridge signal, however, the bridge signal has a temperature dependence which must be compensated due to the high accuracy requirements. In previous embodiments, this is accomplished either by compensation resistors applied to the steel diaphragm or by temperature measurement in the area of the electronic analyzer, subsequently taking into account the output signal calculation.

#### Advantages of the Invention

According to the approach proposed by the present invention, through suitable dimensioning of the diaphragm geometry and

appropriate positioning of strain gauges (DMS) on the diaphragm, the bridge circuit is influenced in such a way that the total resistance of the measurement bridge is independent of the deflection of the diaphragm and thus the total  
5 resistance depends only on the temperature of the diaphragm. Therefore, regardless of the pressure to be measured, the temperature of the diaphragm may be determined using the measurement bridge, i.e., the measurement bridge designed as a Wheatstone bridge, and this temperature may be used for  
10 compensation purposes. Therefore, a pressure-independent temperature measurement of the diaphragm is possible using the measurement bridge functioning as a sensor element without requiring additional compensation-measuring or temperature-measuring resistors to be applied to the metal diaphragm.

15 In an advantageous manner, no additional area of the metal diaphragm is required by compensation-measuring or temperature-measuring resistors and their electrical connection points due to the approach proposed according to the present invention. Therefore, a higher degree of  
20 miniaturization is achievable, which is of considerable importance given the space situation in the cylinder head area of today's internal combustion engines, where pressure sensors are used. Miniaturization of sensor elements also offers advantages with regard to manufacturing costs. The  
25 miniaturized combustion chamber pressure sensors greatly increase the possible applications of such sensor elements in internal combustion engines.

Furthermore, additional electric contact points are eliminated by the approach proposed by the present invention, thereby  
30 greatly simplifying the manufacturing process as well as making it possible to avoid potential failure points, e.g., due to contact breakage. In combustion chamber pressure sensors, the electronic analyzer is located at a great

distance from the actual pressure measurement point, where peak temperatures of up to 600°C may occur, because of the maximum allowed temperature of approximately 140°C. Thus with the pressure sensors used in the past, a temperature  
5 measurement in the area of the electronic analyzer would yield a signal far too inaccurate for temperature compensation of the Wheatstone measurement bridge. The measurement accuracy of the combustion chamber pressure sensor may be greatly improved by measuring and analyzing the pressure-independent bridge  
10 resistance as proposed by the present invention.

#### Drawing

The present invention is described in greater detail below on the basis of the drawing.

Figures 1a, 1b, 1c, 1d show embodiments of strain gauges  
15 (DMS) provided on a metal diaphragm,

Figure 2 shows a metal diaphragm having strain gauges applied thereto in the deflected state and

Figure 3 shows a cross section of the diaphragm material having elongation and compression maximums.

#### 20 Variants of Embodiments

The bridge circuits on a steel diaphragm as shown in the figure sequence 1a, 1b, 1c and 1d represent the current related art.

A bridge circuit 5, which may be designed as a Wheatstone  
25 bridge circuit, is applied to a metal diaphragm 1. Bridge circuit 5 includes multiple resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$ , characterized by reference numerals 6, 7, 8 and 9. Metal diaphragm 1 is preferably a steel diaphragm, the center of

which is labeled as 2, designed in a radius  $r$ . The peripheral areas, i.e., the areas at a greater distance from center 2 of metal diaphragm 1, are each indicated by reference numeral 3. The edge of metal diaphragm 1 is labeled with reference numeral 4.

Resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  connected in bridge circuit 5 are preferably strain gauges. Bridge circuit 5 is connected to a power supply voltage  $U_0$ . Measurement voltage  $U_A$  is tapped between resistors  $R_1$  and  $R_4$  or  $R_2$  and  $R_3$ .

Resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  provided on metal diaphragm 1 are positioned so that they experience an elongation or compression when a pressure acts on metal diaphragm 1. The bridge circuit is tuned in this way, yielding a voltage signal  $U_A$ , which is proportional to the pressure acting on metal diaphragm 1, the voltage signal being sent to an analyzer circuit. This signal  $U_A$  depends not only on pressure but also on temperature. Pressure dependence is desired but the temperature dependence of thus obtained signal  $U_A$  necessitates the use of compensation resistors  $RT_1$ ,  $RT_2$  to meet the high accuracy requirements for use as a combustion chamber pressure sensor. With the approach illustrated in Figure 1, additional compensation resistors  $RT_1$ ,  $RT_2$  are applied to metal diaphragm 1 to compensate for the temperature dependence of measurement signal  $U_A$ . However, these compensation resistors  $RT_1$ ,  $RT_2$  influence only the temperature dependence of the sensitivity but the zero point remains uncompensated. Another possibility for eliminating the temperature dependence which influences signal accuracy is to measure the temperature in the area of the electronic analyzer and to correct output signal  $U_A$  by the temperature influence, thereby improving the accuracy of measurement signal  $U_A$ . However when used as a combustion chamber pressure sensor, the electronic analyzer is located at a great distance from the actual pressure measurement point,

where peak temperatures of 600°C occur, because of its temperature limitation of approximately 140°C. The signal obtained by temperature measurement in the area of the electronic analyzer is therefore far too inaccurate for temperature compensation of the bridge circuit due to the temperature limitation on the electronic analyzer. In the variants depicted in Figures 1a, 1b, 1c and 1d, compensation resistors  $RT_1$ ,  $RT_2$  which are additionally used (optionally) require an increased amount of space on the metal diaphragm while also necessitating an additional contacting pad.

The diagram according to Figure 2 shows the configuration of a bridge circuit proposed according to the present invention, applied to a metal diaphragm.

Metal diaphragm 1 shown in Figure 2 is preferably a steel diaphragm including a center 2 and peripheral areas 3 extending radially. Metal diaphragm 1 is bordered by edge 4 and is provided with bridge circuit 5 which is designed according to the embodiment known from the related art as depicted in Figure 1. Bridge circuit 5 is also designed as a Wheatstone bridge and includes four interconnected resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$ , identified by reference numerals 6, 7, 8 and 9. Bridge circuit 5 is supplied with power by a power supply voltage  $U_0$ ; the voltage tap for the resulting measurement signal, i.e., measurement voltage  $U_A$ , takes place between resistors  $R_1$  and  $R_4$  on the one hand and resistors  $R_2$  and  $R_3$  on the other hand.

Resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  are preferably designed as strain gauges. The positions where resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  are applied to the metal diaphragm 1 may be determined with the help of the finite element method (FEM). After creating a geometric model of metal diaphragm 1 and defining suitable boundary conditions, the finite element method yields as the

result the elongation topology of metal diaphragm 1 under compressive stress.

In addition to other optimization parameters, the boundary conditions under which the finite element method is used also  
5 take into account the fact that the radial elongation of metal diaphragm 1 is equal in absolute value to the compression ( $\epsilon_{\text{compress}}$ ) of metal diaphragm 1. In addition, the nominal pressure acting upon metal diaphragm 1 may also be taken into account as a modulation parameter. As geometric boundary  
10 conditions, the diameter of metal diaphragm 1 and the diaphragm thickness are taken into account. The diaphragm thickness may also vary in the radial direction, which may be taken into account as an influencing parameter in the finite element method. In addition, the diaphragm height of metal  
15 diaphragm 1 and the properties of the material of which metal diaphragm 1 is made may also be taken into account. In addition to designing the diaphragm as metal diaphragm 1, it may also be made of a ceramic material.

Areas in which both the elongation maximums and the  
20 compression maximums occur when pressure is acting on metal diaphragm 1 arise from the elongation topology of metal diaphragm 1. Maximum elongation 12 typically occurs at center 2 of metal diaphragm 1 because it is at the greatest distance from the clamping point, i.e., edge 4 of metal diaphragm 1,  
25 and consequently may be deflected to the greatest extent by the pressure acting on metal diaphragm 1. Compression maximums 13 are usually located in peripheral area 3 of metal diaphragm 1, i.e., they are usually in the area of edge 4 of metal diaphragm 1 which is preferably designed as a steel diaphragm.  
30 The boundary conditions of FEM simulation are advantageously selected so that, following geometric optimization, maximum elongation 12 occurring at center 2 of metal diaphragm 1 corresponds in absolute value to the absolute values of

compression maximums 13 in peripheral area 3 of metal diaphragm 1. The positions of four resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  may be selected on the basis of the elongation topology determined by the geometric model and optimized by suitable shaping of metal diaphragm 1 so that the absolute values of elongations  $\Delta l$  correspond to those of compressions  $-\Delta l$ .

In these positions, which are determined by determination of the elongation topology of metal diaphragm 1, four resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  designed as strain gauges are situated on metal diaphragm 1. When the four resistors of bridge circuit 5 are provided on metal diaphragm 1 in the positions shown in Figure 2, the change in resistance under compressive stress on all four resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  is identical in terms of absolute value. The diagram in Figure 2 shows that both resistors  $R_1$  and  $R_3$  identified by reference numerals 6 and 8, respectively, are situated in the area of metal diaphragm 1 near the center, forming a pair of resistors 10 near the center. The two resistors are stretched from their original length to a length  $l + \Delta l$  because of the elongations prevailing in the area of center 2 of the pressure action on metal diaphragm 1. Stretching  $\Delta l$  (i.e., the elongation) of two resistors  $R_1$  and  $R_3$  designed as strain gauges is identical. Instead of the orientation of two resistors  $R_1$  and  $R_2$  as shown in Figure 2, they may be situated parallel to the horizontal axis or parallel to the vertical axis of metal diaphragm 1. However, the positions of a peripheral resistor pair 11 are located in periphery 3 of metal diaphragm 1 and in the areas where compression maximums 13 occur. When pressure acts on metal diaphragm 1 from one side, resistor pair 10 near the center is under elongation stress, i.e., is stretched by amount  $\Delta l$ .

Peripheral resistor pair 11 is compressed by distance  $-\Delta l$ , as indicated by the dotted line representing two resistors  $R_2$



and/or  $R_4$ . Compression  $l - \Delta l$  indicates the length by which two resistors  $R_1$  and/or  $R_4$  which are in the compression area of metal diaphragm 1 are compressed by pressure acting on metal diaphragm 1. The stretching of two resistors  $R_1$  and  $R_3$  situated near the center, forming resistor pair 10 near the center, is represented by  $l + \Delta l$  and is also indicated by dashed lines. Due to the arrangement of resistor pair 10 near the center and peripheral resistor pair 11, absolute value  $\Delta l$  of compressed resistors  $R_2$  and  $R_4$  is identical to length  $\Delta l$  of resistor pair 10 situated near the center. Because of this fact, tensile elongations  $\Delta l$  of two resistors  $R_1$  and  $R_3$  near the center correspond to compressions  $-\Delta l$  of resistors  $R_2$  and  $R_4$  which are situated farther to the outside in periphery 3 of metal diaphragm 1 and are under compressive stress. In this case, the total resistance of bridge circuit 5 depends only on the temperature and is thus independent of the applied pressure which is to be determined by the deflection of metal diaphragm 1. Thus the temperature of bridge circuit 5 may be determined by measuring total resistance  $R_{TOT}$  and may then be used for compensating the temperature influence.

The arrangement of resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  illustrated in Figure 2 on the basis of an example results in the total resistance of bridge circuit 5 becoming independent of the deflection of metal diaphragm 1 and thus depends only on the temperature of metal diaphragm 1. Therefore, regardless of the pressure to be measured, the temperature of metal diaphragm 1 may be determined using bridge circuit 5 and used for compensation purposes. This ensures that the temperature to which bridge circuit 5 is exposed is the true temperature by whose influence resulting measurement signal  $U_A$  of bridge circuit 5 is to be compensated. Measurement inaccuracies due to temperature compensation in the area of the electronic analyzer, which is situated at a great distance from metal

diaphragm 1 for reasons of thermal stress, may be eliminated directly by the temperature compensation proposed by the present invention by the design, i.e., the positioning, of resistors  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  of bridge circuit 5. Thus the approach proposed by the present invention makes it possible to achieve a significantly more accurate pressure-independent temperature determination of metal diaphragm 1. In contrast with the approach known from the related art, additional compensation-measuring or temperature-measuring resistors may be omitted due to the use of the approach proposed by the present invention. Furthermore, the combustion chamber area required to apply the compensation-measuring or temperature-measuring resistors is eliminated so that the electric connection points for the compensation-measuring and temperature-measuring resistors may also be omitted. Thus, on the whole, metal diaphragm 1 may be designed to be much smaller because much less area is needed. The elimination of the electric contacting points of the additional compensation-measuring or temperature-measuring resistors known from the approaches in the related art prevents weaknesses that would be potential failure points.

The diagram in Figure 3 is a cross section of the diaphragm material showing the position of the elongation maximums and compression maximums.

Metal diaphragm 1 shown partially in cross section in Figure 3 is symmetrical to axis of symmetry 14. The diaphragm material may be a metallic material or a ceramic material. When pressure acts on metal diaphragm 1, it assumes the form illustrated in Figure 3. Metal diaphragm 1 is elongated in the area of center 2 and is compressed at periphery 3. The position of resistor 10 near the center is indicated by reference numeral 16 in Figure 3 while the position of resistor pair 5 at a distance from the center, situated in

periphery 3 of metal diaphragm 1, is indicated by reference numeral 17. Owing to the geometric deformation of diaphragm material 15, center 2 undergoes elongation in the radial direction. Radial elongation  $\epsilon_{r, \text{elong}}$  which occurs at center 2 of metal diaphragm 1 corresponds in terms of absolute value to radial compression  $\epsilon_{r, \text{compress}}$  in the area of periphery 3 of metal diaphragm 1. The elongation in the radial direction in radial elongation area 18 corresponds in absolute value to radial compression  $\epsilon_{r, \text{compress}}$ , indicated by reference numeral 19 in peripheral area 3 of metal diaphragm 1.

## List of reference numerals

1	Metal diaphragm
2	Center
3	Periphery
4	Edge
$U_0$	Power supply voltage
$U_A$	Output voltage $U_0$
5	Bridge circuit
6	First resistor ( $R_1$ )
7	Second resistor ( $R_2$ )
8	Third resistor ( $R_3$ )
9	Fourth resistor ( $R_4$ )
$RT_1$	First temperature compensation resistor
$RT_2$	Second temperature compensation resistor
10	Pair of resistors ( $R_1, R_3$ ) near the center
11	Peripheral resistor pair ( $R_2, R_4$ )
$\Delta l$	Elongation of resistors near the center
$-\Delta l$	Compression of peripheral resistors
$ \Delta l $	Absolute value of elongation/compression
12	Elongation maximum
13	Compression maximum
14	Axis of symmetry
15	Diaphragm material
$E_r$	Radial elongation
16	Position of resistor pair near the center
17	Position of resistor peripheral from the center
18	Radial elongation area $\epsilon_{r, \text{elong}}$
19	Radial compression area $\epsilon_{r, \text{compress}}$